E. Energy Absorption in Adhesively Bonded Composites

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Objectives

- Develop a comprehensive experimental and analytical methodology to analyze and design adhesively bonded automotive composite structures to sustain axial, off-axis, and lateral crash/impact loads.
- Determine the rate sensitivity of bonded tubes to crush through experiments on the ORNL Test Machine for Automotive Crashworthiness (TMAC).
- Determine influence of critical joint design parameters, for example, bond length, bond thickness, and fillet, on specific energy absorption.
- Experimentally determine the full-field deformations at joint discontinuities for validation of analytical/numerical results.

Approach

- Coordinate with the bonded joint experimental and analytical efforts undertaken in ACC project Composite Crash Energy Management.
- Select a substrate, adhesive, and representative subcomponent joint geometry for evaluation.

- Characterize substrate material, adhesive material, and coupon level joints under static and dynamic loads.
- Build and test unbonded and bonded rail components under static and dynamic crush loads.
- Correlate experimental results with analytical results by developing finite-element-based tools with appropriate material models and progressive damage algorithms.
- Enhance the understanding of joint performance by conducting full-field deformation measurements using moiré interferometry.

Accomplishments

- Fabricated near void-free bulk adhesive panels and cylindrical rods for adhesive characterization studies.
- Fabricated tensile, compression, compact tension (fracture toughness), and shear specimens.
- Characterized tensile and compressive response and fracture toughness of bulk adhesive at quasi-static load rates.

Future Direction

- Design and fabricate required test fixtures for conducting dynamic tests on TMAC.
- Complete static and dynamic testing of substrate, bulk adhesive, and coupon level joints.
- Install and set-up moiré interferometric test equipment for characterizing full-field deformation patterns in adhesive joints.

Introduction

The objective of this project is to develop a comprehensive experimental and analytical methodology to analyze and design adhesively bonded automotive composite structures to sustain axial, off-axis, and lateral crash loads. This direct-funded project will be closely aligned with the experimental and analytical efforts undertaken in ACC 100 (7D) for composite substrates. The focus of this work, however, will be restricted to the adhesive joint related issues. The key to the methodology development is the understanding of how critical joint design parameters, for example, bond length, bond thickness, and fillet, affect the energy absorption. Recent investigations at ORNL have provided valuable insight toward the understanding of composite joint performance and composite crashworthiness. The next logical step is determining the correlation between measurable adhesive joint parameters and their influence on the structure to dissipate energy and ultimately predict crashworthiness for a particular composite design.

Experimental tasks include material testing under quasi-static and dynamic loads for substrates, adhesives, and joints; full-field deformation mapping of joints with moiré interferometry for correlation with computational results; strain-rate sensitivity studies; fracture toughness testing; and test method development as required. These experimental results will provide the building blocks for model developments—first at the coupon level, then progressing in complexity to component level. Correlation with experimental results will provide the basis for which the analytical developments including development of constitutive laws, materials models, damage algorithms, and new finite elements will be made. Structural tests will be conducted on the new intermediate-rate test machine (TMAC) at ORNL (7.C).

Project Deliverables

At the end of this multiyear program, joint parameters that have significant influence on energy dissipation will be identified, and their influence quantified, using appropriate analytical models and experimentation. In collaboration with the ACC Composite Crash Energy Management project, a predictive capability for joint performance will be demonstrated, and the validity of the prediction will be assessed through structural crash testing.

Approach and Results

The technical approach involves both experimental and analytical tasks. There are four main tasks:

- Task 1—Materials Selection and Screening,
- Task 2—Material Characterization,
- Task 3—Component Testing, and
- Task 4—Computational Tools Development.

Task 1 was completed and reported on in the FY 2002 annual report. The selected chopped carbon fiber prepreg material system was characterized from flat plaques provided by the vendor. Discussions with the vendor lead to an overly optimistic view of the suitability of the material for this project. Additionally, delays in receipt of the material from the supplier resulted in consideration of a carbon fiber sheet molding component (SMC). Both materials are unsatisfactory due to processing difficultly and material variability. As a result of the variability in the initial material screening tests and difficulty in fabricating tubes with this material, the substrate material was changed to a carbon fiber braided system. The woven fabric prepreg is comprised of T300B carbon fiber with a tow size of 3K and 42% (by weight) epoxy resin.

Task 2 was initiated during FY 2002 and was originally scheduled to be completed in the third quarter of FY 2003. The schedule has been adversely impacted by several factors, including delays in substrate material acquisition due to supplier manufacturing constraints and then actually changing the substrate (discussed above), laboratory-initiated relocation of test facilities from Y-12 National Nuclear Security Complex to ORNL, operation constraints on TMAC pending pressure vessel certification, and budget constraints. A new schedule is being prepared that takes into account the impact of all these factors.

The substrate will be fully characterized by conducting tension, compression, and in-plane shear tests. The degree of anisotropy in the material will be qualified by testing specimens that are machined from two different orthogonal directions in the panels. This work will be contracted out to an independent testing laboratory by the ACC.

The adhesive used in this study is an epoxy paste designated as Sovriegn PL731 and is used in many of the research projects within the ACC. The bulk adhesive testing consists of tension, compression, shear, and fracture toughness. In addition, DSC/DMA tests will be conducted to verify the degree of cure. The key to this task is the successful fabrication of high-quality specimens (e.g., low void content) to accurately quantify the bulk adhesive mechanical properties. The compression and shear testing will be accomplished using cylindrical rod specimen geometries. Cylindrical rod specimens were fabricated using centrifugation and glass test tubes as molds. Initial difficulties in producing flat plaques were alleviated by developing a mold-filling process that uses an adequate supply of excess adhesive under pressure to back fill the mold cavity. High-quality specimens for all bulk adhesive tests were fabricated with these two approaches.

Characterization of the tensile and compressive responses is complete and indicates excellent consistency from specimen to specimen and from plaque to plaque. Tensile results for 18 samples from two different plaques indicate average ultimate strength and modulus for the adhesive is 7.3 ksi and 0.31 Msi, respectively. Coefficients of variability (COVs) for the strength and modulus results are 4.8% and 1.6%, respectively, which is excellent. A typical tensile stress strain curve for this adhesive is shown in Figure 1.

Eight cylindrical samples—1 in. long, 0.5-in. diameter—were subjected to compressive loads (ASTM D695) up to strains of 22% without global failure. Compressive modulus for the adhesive, taken from a range of 1% to 2% strain, is 0.31 Msi, identical to the tensile value. The COV is 1.6%, consistent with the tensile results. Figure 2 depicts representative

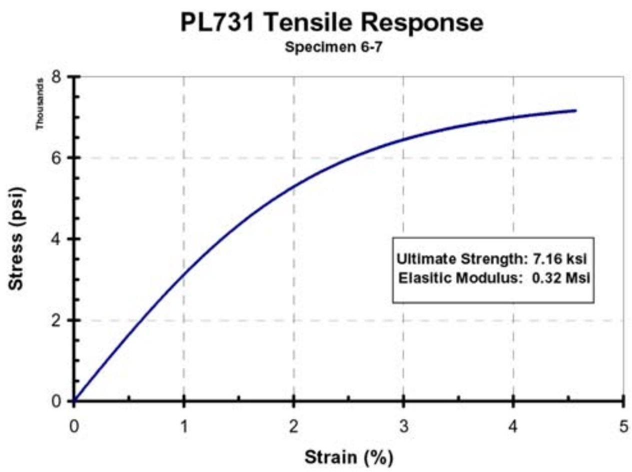

Figure 1. Typical tensile stress-strain curve for the bulk adhesive.

Figure 2. Typical posttest condition of compression samples, indicating plastic deformation and local cracking associated with large strains.

"failed" test samples that indicated plastic deformation with small local cracks being present in some samples. Figure 3 illustrates the consistency of the compressive response out to more than 20% strain.

Preliminary quasi-static and low-speed dynamic fracture toughness tests were completed using the compact tension specimen geometry. The specimens were machined from an 8-mm-thick bulk adhesive plaque per the geometry specified in ASTM D5045. The technique developed for making near void-free 3-mm-thick plaques was also used for making these plaques. The tests were conducted on a conventional closed-loop servo-hydraulic machine at rates of 0.02, 2.5, 25, and 1000 mm/s with three specimens tested at each rate. An untested and a tested specimen are shown in Figure 4, and a typical load-displacement curve for the quasi-static tests is shown in Figure 5. The apparent fracture toughness of the bulk adhesive was estimated using the maximum load, and the average results at each load rate are plotted in Figure 6. There appears to be an initial drop in the fracture toughness as a function of load rate but the initial quasi-static value appears to be much greater than typical values for epoxy systems. Consequently, the experimental data and test methodology are being evaluated for their validity.

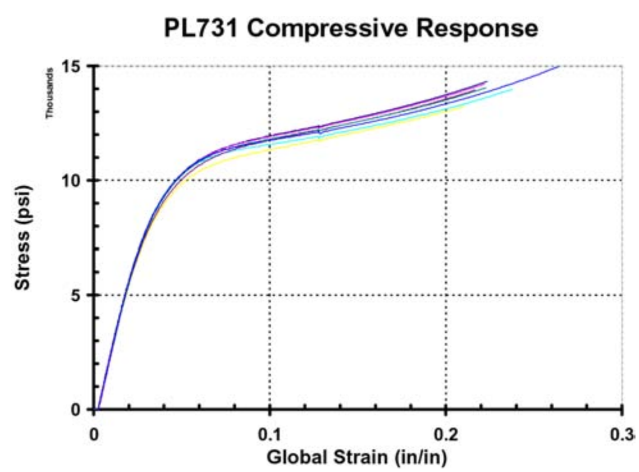

Figure 3. Combined compressive stress-strain curves for the bulk adhesive (eight samples).

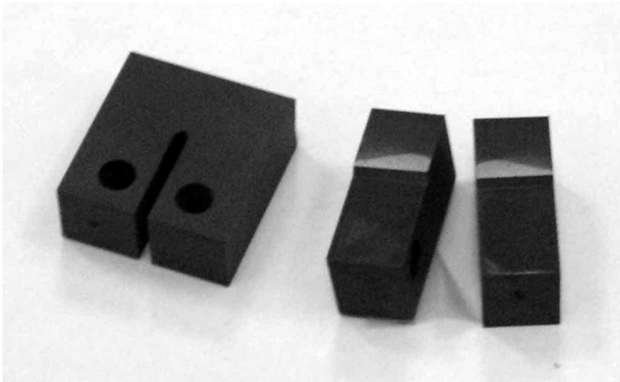

Figure 4. An untested and a tested bulk adhesive compact tension specimen.

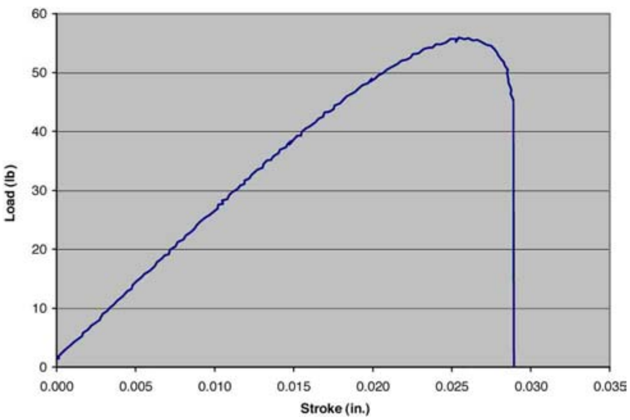

Figure 5. Load-displacement data from quasi-static compact tension test on bulk adhesive.

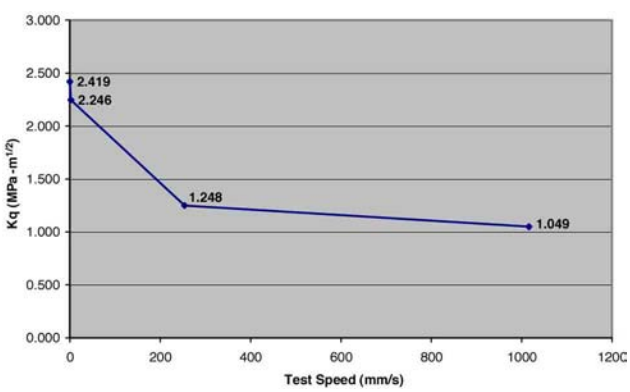

Figure 6. Apparent bulk adhesive fracture toughness as a function of testing rate.

Coupon-level joint configurations will consist of double-notch shear (DNS) and single-lap shear (SLS) test specimen geometries. Joint parameters that will be investigated are the adhesive thickness, overlap length, and fillet geometry. Moire interferometry will be used to study the full-field deformation pattern in the bond-line during static testing of the SLS joint specimens. The crack growth characteristics of an adhesive joint will be quantified by conducting Mode I, Mode II, and Mixed Mode fracture tests using double cantilever beam (DCB), end-notch flexure (ENF), and mixed-mode bending (MMB) specimen geometries, respectively.

Component testing in Task 3 was scheduled to commence in the last half of FY 2003 but will likely be delayed due to the issues stated above. Component testing will consist of unbonded and adhesively bonded upper rail sections. The testing will include static and dynamic crush loads, and axial and lateral impact loads. The TMAC at ORNL and test sleds will be used for the dynamic testing. The unbonded tests are to establish a baseline, and then the results from Task 2 will guide the joint design such that bonded sections will be built to either fail or not fail in the joint. Some of these tests will be repeated using scaled geometries to get an initial look at scale effects.

In Task 4, the computational tools development will consist of analyzing the test geometries at both the coupon level and component level, developing new material models, and developing new test methods to support the model development. This task is conducted in parallel with Tasks 2 and 3. The coupon and component level analyses will be completed using existing material models that are available in FEA tools such as ABAQUS and LS-DYNA. The bond-line deformations predicted by the analyses will be compared with the Moire experimental results. Also, the effects of bond-line thickness and length, fillet, and loading rate on the stress distribution in the joint will be correlated with the experimental results. The model development effort will consider new constitutive laws, progressive damage algorithms, new finite elements for modeling the adhesive layer, and new computationally efficient techniques. In support of this effort, new test methods will be developed for characterizing strain-rate effects and dynamic fracture

Summary

Highlights of the progress during this reporting period follow:

1. Manufactured all bulk adhesive samples for tension, compression, shear, and fracture tests.
2. Completed bulk adhesive tensile and compression tests. Results indicate excellent consistency. Data have been supplied to the ACC partners for implementation in the FEA.
3. Completed preliminary fracture toughness tests on bulk adhesive, and the results are being reviewed by the project team for their validity.
4. The chopped carbon fiber substrate material was replaced with a carbon fiber braided material as a result of excessive variability in the chopped fiber material data and inability to fabricate high-quality tubular specimens.